

# Comparison of the electron-spin-resonance linewidth in multilayered CuMn spin glasses with insulating versus conducting interlayers

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The temperature-dependent electron-spin-resonance linewidth  $\Delta H(T)$  may be used to investigate the effect of the geometry and interlayer material on the magnetic properties of multilayered systems. We compare  $\Delta H(T)$  in CuMn/Al<sub>2</sub>O<sub>3</sub> multilayers with previous measurements of CuMn/Cu samples. CuMn/Al<sub>2</sub>O<sub>3</sub> samples with CuMn thicknesses,  $W_{SG}$ , from 40 Å to 20 000 Å obey the same form as the CuMn/Cu system, but show quantitative differences in the fitting parameters. The linewidths of the CuMn/Al<sub>2</sub>O<sub>3</sub> samples, even in the bulk, are systematically larger than the linewidths for the CuMn/Cu samples, suggesting that the ESR linewidth is sensitive to differences in sample growth and structure. The value of the minimum linewidth decreases with decreasing  $W_{SG}$  in the CuMn/Al<sub>2</sub>O<sub>3</sub> series, but remains constant in the CuMn/Cu series. Although susceptibility measurements of the freezing temperature  $T_f$  do not differentiate between samples with  $W_{SG} \geq 5000$  Å, the ESR linewidth is sensitive to changes at larger length scales. This experiment emphasizes the importance of considering both the total sample thickness, as defined by the range of the conduction electrons, and the spin-glass layer thickness in analyzing the ESR linewidth in multilayers.

## INTRODUCTION

Finite-size and dimensionality effects in multilayered spin glasses have been shown to depend on the interlayer material, especially when the spin-glass layer thickness  $W_{SG}$  becomes small.<sup>1-3</sup> We have previously demonstrated that the temperature-dependent electron-spin-resonance linewidth in multilayered CuMn/Cu systems<sup>4,5</sup> provides detailed information about spin relaxation rates. In this article, we compare the temperature dependence of the electron-spin-resonance linewidth  $\Delta H(T)$  in Cu<sub>0.92</sub>Mn<sub>0.08</sub>/Al<sub>2</sub>O<sub>3</sub> multilayers with previous measurements of the Cu<sub>0.93</sub>Mn<sub>0.07</sub>/Cu system.

## DATA AND ANALYSIS

Cu<sub>0.92</sub>Mn<sub>0.08</sub>/Al<sub>2</sub>O<sub>3</sub> samples, with  $40 \text{ Å} \leq W_{SG} \leq 20\,000 \text{ Å}$ , were fabricated at the Johns Hopkins University using dc and rf sputtering. Cu<sub>0.93</sub>Mn<sub>0.07</sub>/Cu samples were fabricated by dc sputtering at Michigan State University. In both cases, the interlayer thicknesses are held constant at values large enough (75 Å for Al<sub>2</sub>O<sub>3</sub> and 300 Å for Cu) to prevent coupling between the CuMn layers.

The depression of the spin-glass freezing temperature,  $T_f$ , with decreasing  $W_{SG}$  is described in terms of  $\epsilon$ , with

$$\epsilon = \left( \frac{T_f(\infty) - T_f(W_{SG})}{T_f(\infty)} \right). \quad (1)$$

$T_f(\infty)$  is the freezing temperature of the bulk. Finite-size scaling predicts<sup>6</sup>  $\epsilon \propto W_{SG}^{-1/\nu}$ . A crossover from three-dimensional (3D) to two-dimensional (2D) behavior has been demonstrated by frequency dependent<sup>7</sup> and nonlinear susceptibility measurements.<sup>3,8</sup> Figure 1 compares the depression of  $T_f(W_{SG})/T_f(\infty) = 1 - \epsilon$  for insulating and conduct-

ing interlayers. Solid lines show fits to Eq. (1) with  $\nu=1.3$  for CuMn/Cu samples<sup>4</sup> and  $\nu=1.6$  for CuMn/Al<sub>2</sub>O<sub>3</sub> samples.<sup>3</sup> The depression of  $T_f$  in CuMn/Al<sub>2</sub>O<sub>3</sub> multilayers is similar to that observed in CuMn/Si.<sup>9</sup>

Above  $T_f$ ,  $\Delta H(T)$  in spin glasses is described by a superposition of two behaviors—a linear temperature dependence and a critical divergence as  $T_f$  is approached.

$$\Delta H(T) = A + BT + C \left( \frac{T - T_f}{T_f} \right)^{-\kappa}. \quad (2)$$

In Eq. (2),  $A$  is the residual linewidth,  $B$  the thermal broadening coefficient,  $C$  the divergence strength, and  $\kappa$  a critical exponent. The  $A + BT$  behavior reflects the relative magnitudes of relaxation rates between the localized moments, conduction electrons, and lattice.<sup>10,11</sup> In particular, the thermal broadening coefficient  $B$  can be modeled to include ef-

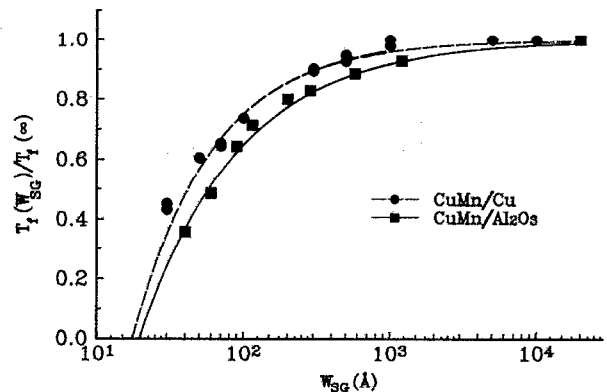


FIG. 1. The depression of the freezing temperature,  $T_f(W_{SG})$ , normalized to the bulk value,  $T_f(\infty)$  as a function of  $\log_{10}(W_{SG})$  for CuMn/Al<sub>2</sub>O<sub>3</sub> (triangles) and CuMn/Cu (circles). Solid lines are fits to finite-size scaling.

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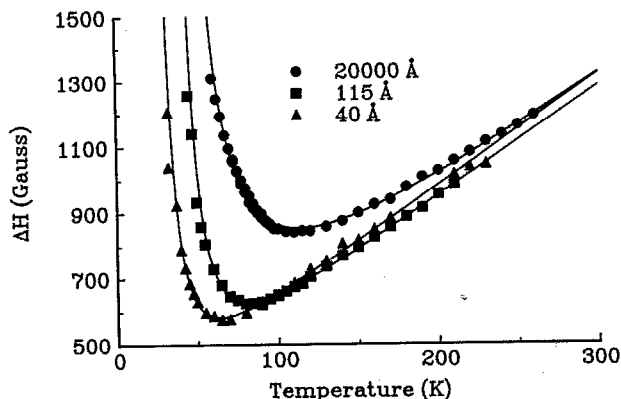


FIG. 2. Dependence of the ESR linewidth in CuMn/Al<sub>2</sub>O<sub>3</sub> on temperature for CuMn layer thicknesses of 20 000 Å (circles), 115 Å (squares), and 40 Å (triangles). Solid lines represent fits to Eq. (2).

fects due to interfaces and surfaces.<sup>4</sup> The linewidth diverges as  $T_f$  is approached, with  $\kappa \approx 1.5$  in the bulk.<sup>5</sup>

Previous measurements<sup>4,5</sup> of  $\Delta H(T)$  in the CuMn/Cu system shows that the behavior described by Eq. (2) is obeyed for  $10 \text{ Å} \leq W_{SG} \leq 10\,000 \text{ Å}$ , with systematic changes in the parameters as a function of  $W_{SG}$ . Samples with  $W_{SG} < \text{about } 50 \text{ Å}$  fit preferentially to a two-dimensional form ( $T_f \rightarrow 0$ ) of Eq. (2). The data may be parametrized<sup>4</sup> in terms of  $\epsilon$ , with both  $A$  and  $B$  increasing linearly with  $\epsilon$ . The crossover of the critical behavior from the 3D to 2D limit can be described by a continuous function of  $\epsilon$ . The detailed information obtained from this study indicates that ESR is useful for studying the dependence of  $\Delta H(T)$  on interlayer material.

Figure 2 shows  $\Delta H(T)$  for a 20 000-Å CuMn film, and multilayered CuMn/Al<sub>2</sub>O<sub>3</sub> samples with  $W_{SG} = 115 \text{ Å}$  and  $40 \text{ Å}$ . The solid lines represent fits to Eq. (2), with the fitting parameters shown in Table I. The sample with  $W_{SG} = 40 \text{ Å}$  fits preferentially to the  $T_f = 0$  form, with the exponent from this fit shown in parenthesis in Table I.<sup>12</sup>

With the exception of the residual linewidth  $A$ , which remains approximately constant, all parameters obey the same general trends with decreasing  $W_{SG}$  as those from the CuMn/Cu series. The magnitudes of the thermal broadening coefficients  $B$  are comparable to those observed in the

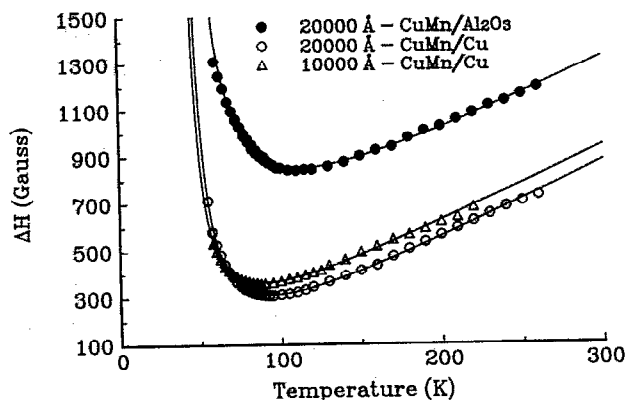


FIG. 3. Comparison of the ESR linewidth as a function of temperature for the 20 000-Å film from the CuMn/Al<sub>2</sub>O<sub>3</sub> series (solid circles), and 20 000-Å (open circles) and 10 000-Å (open triangles) films from the CuMn/Cu series. Solid lines are fits to Eq. (2).

CuMn/Cu samples. The values of  $\kappa$ , while comparable in the bulk, are larger in the CuMn/Al<sub>2</sub>O<sub>3</sub> multilayers, as are the divergence strengths. Extension of these measurements to a greater range of  $W_{SG}$  is necessary to determine if the parameters follow the same dependence on  $\epsilon$  as CuMn/Cu.<sup>13</sup>

Distinct differences between the two sets of samples are observed. Figure 3 compares the temperature dependence of  $\Delta H(T)$  for 20 000-Å films from the CuMn/Cu (Ref. 14) and the CuMn/Al<sub>2</sub>O<sub>3</sub> series. The values of the parameters from fitting the CuMn/Cu sample to Eq. (1) are also shown in Table I. The linewidths for the CuMn/Al<sub>2</sub>O<sub>3</sub> series are approximately 500-G larger than those of the corresponding CuMn/Cu data. The magnitude of the difference in the linewidths cannot be explained by the concentration difference, which is less than 1 at. %. Table I shows that the thermal broadening coefficients and values of  $\kappa$  are the same for both 20 000-Å samples, but that the residual linewidths and divergence strengths are different. Comparison of sample-growth parameters indicates no obvious differences that might explain these results.

The second significant difference between Al<sub>2</sub>O<sub>3</sub> and Cu interlayers is that the CuMn/Al<sub>2</sub>O<sub>3</sub> series shows a decrease in the magnitude of the minimum linewidth with decreasing  $W_{SG}$ . The minimum linewidth of the CuMn/Cu series was approximately constant for all  $W_{SG}$ .<sup>4,5</sup> In the CuMn/Cu system, scattering from CuMn/Cu boundaries is negligible compared to CuMn/air boundaries and we expect surface effects due to the total sample thickness to dominate. In samples with insulating interlayers, the electrons are restricted to the CuMn layers and  $W_{SG}$  should be the dominant length. The constant values of the minimum linewidth in the CuMn/Cu series may be the result of all samples having approximately the same total thickness. This illustrates the need to consider both the total sample thickness and the spin-glass layer thickness, as the type of interlayer material will determine which length scale is dominant. Detailed conclusions are prohibited by the complicated dependence of the value of the minimum linewidth on the parameters of Eq. (2).

The dependence of  $\Delta H(T)$  on the total sample thickness was studied by Nagashima and Abe<sup>15</sup> in Cu<sub>1-x</sub>Mn<sub>x</sub> ( $x = 0.01$

TABLE I. Parameters obtained by fitting to Eq. (1).

$W_{SG}$ (Å)	$T_f$ (K)	$A$ (G)	$B$ (G/K)	$C$ (G)	$\kappa$
Cu <sub>0.92</sub> Mn <sub>0.08</sub> /Al <sub>2</sub> O <sub>3</sub>					
20 000	35	296	3.31	561	1.4
115	25	285	3.32	594	2.6
40	12.5	306	3.38	3601	2.9 (3.8) <sup>a</sup>
Cu <sub>0.93</sub> Mn <sub>0.07</sub> /Cu					
20 000	37	-133	3.31	241	1.40
10 000	37	-43	3.23	184	1.35

<sup>a</sup>The value in parenthesis for the 40-Å sample represents the exponent obtained by fitting to the 2D ( $T_f = 0$ ) form of Eq. (1). In this fit, the values of  $A$  and  $B$  remain the same and the prefactor of the divergence does not correspond directly to  $C$ . See Ref. 4 for details and the CuMn/Cu data.

and 0.055 at. %) films of thicknesses from 1000 Å to 50 000 Å. They found an increase in both the minimum value of the linewidth and in  $A$ , the residual linewidth, with decreasing  $W_{SG}$ . This is attributed to the increased importance of surface scattering relative to bulk scattering as the film thickness decreases. Nagashima and Abe did not investigate the divergence of the linewidth, so extracting reliable values for  $A$  and  $B$  for comparison to the present data is difficult.

The open triangles in Fig. 3 represent  $\Delta H(T)$  for a 10 000-Å CuMn film from the CuMn/Cu series and are consistent with the behavior observed by Nagashima and Abe. Parameters from fitting to Eq. (2) are included in Table I. The values of  $\kappa$  are comparable for the two films, but the divergence strengths  $C$  are different. A detailed study of the dependence of these parameters on film thickness is required to determine the origin of these variances, whether the behavior is due to finite size or surface effects, and if the approach to the freezing transition is affected even on this larger length scale.

## CONCLUSION

We have reported measurements of the ESR linewidth as a function of temperature in multilayered  $\text{Cu}_{0.92}\text{Mn}_{0.08}/\text{Al}_2\text{O}_3$  samples with  $20\,000\text{ Å} \geq W_{SG} \geq 40\text{ Å}$ . We find that these data are qualitatively consistent with measurements from CuMn/Cu multilayers, but quantitatively differ. Differences between the magnitudes of the linewidths in samples fabricated at different locations suggest that this technique is sensitive to details of sample fabrication, which may include homogeneity, structure, and purity. The comparison of insulating versus conducting interlayers emphasizes the presence of two significant length scales—the total sample thickness as determined by the range of the conduction electrons and the spin-glass layer thickness. Our preliminary examination of CuMn films confirms that the electron-spin-resonance linewidth is sensitive to changes in the total thickness in samples showing no depression in  $T_f$ . We believe that study of these parameters as a function of interlayer material can provide a convenient framework within which to understand the importance of the different length scales.

Although interpretation of the temperature-dependent ESR linewidth is complicated, this technique has the poten-

tial to provide detailed information on relaxation processes not available from other types of measurements. Further effort must be given to extending the theory of electron-spin resonance in multilayered structures to fully utilize this technique.

## ACKNOWLEDGMENTS

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- <sup>13</sup>A. Gavrin (unpublished). The values of  $\kappa$  in the CuMn/ $\text{Al}_2\text{O}_3$  increase faster with  $W_{SG}$  than the corresponding CuMn/Cu samples. One explanation may be that the  $\text{Al}_2\text{O}_3$  interlayered samples approach 2D behavior at larger values of  $W_{SG}$  than CuMn/Cu samples.
- <sup>14</sup>A minor difference between the samples is that the film from the CuMn/Cu series shown in Fig. 3 is capped with 100 Å of Cu on the top and bottom of the film to protect the sample from oxidation and diffusion of silicon from the substrate. Measurements of films without the protective layer show linewidths that are slightly lower than in the sample with the protective layers.
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